

Review on Flavor Constraints on New Physics Models

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Low Energy Flavor and CP Constraints

Kaons

- ▶ Kaon mixing (ΔM_K , ϵ_K)
- ▶ $K \rightarrow \pi \nu \bar{\nu}$, $K \rightarrow \pi \ell^+ \ell^-$
- ▶ ϵ'/ϵ
- ▶ ...

Charm

- ▶ Charm mixing ($x, y, |q/p|, \phi$)
- ▶ ...

Electric Dipole Moments

- ▶ electron, muon
- ▶ proton, neutron
- ▶ Mercury, Radium, YbF, Francium, ...
- ▶ ...

Leptons

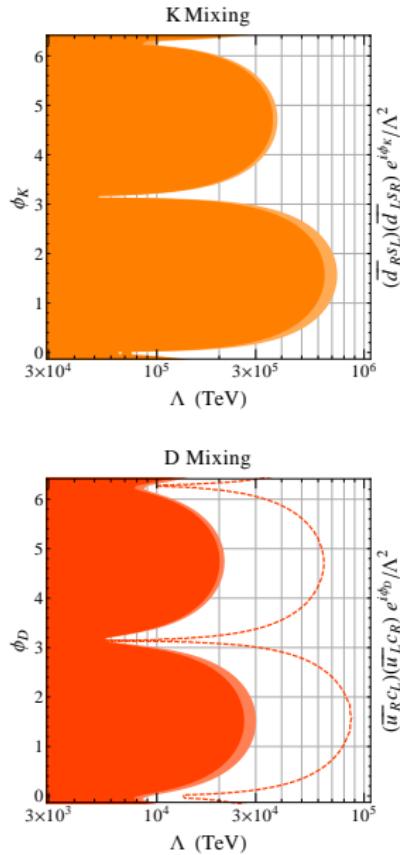
- ▶ $\mu \rightarrow e$ conversion
- ▶ $\ell \rightarrow \ell' \gamma$, $\ell \rightarrow \ell' \ell' \ell'$
- ▶ ...

B Mesons

- ▶ B_d and B_s mixing ($\Delta M_{d,s}$, $S_{\psi K_s}$, ϕ_s)
- ▶ $B_d \rightarrow \mu^+ \mu^-$, $B_s \rightarrow \mu^+ \mu^-$
- ▶ $B \rightarrow X_s \gamma$, $B \rightarrow K^* \gamma$
- ▶ $B \rightarrow X_s \ell^+ \ell^-$, $B \rightarrow K^{(*)} \ell^+ \ell^-$
- ▶ $B \rightarrow X_s \nu \bar{\nu}$, $B \rightarrow K^{(*)} \nu \bar{\nu}$
- ▶ $B \rightarrow \phi K_0$, $B \rightarrow \eta' K_0$, $B_s \rightarrow \phi \phi$
- ▶ $B \rightarrow \tau \nu$, $B \rightarrow D^{(*)} \tau \nu$
- ▶ ...

Meson Mixing

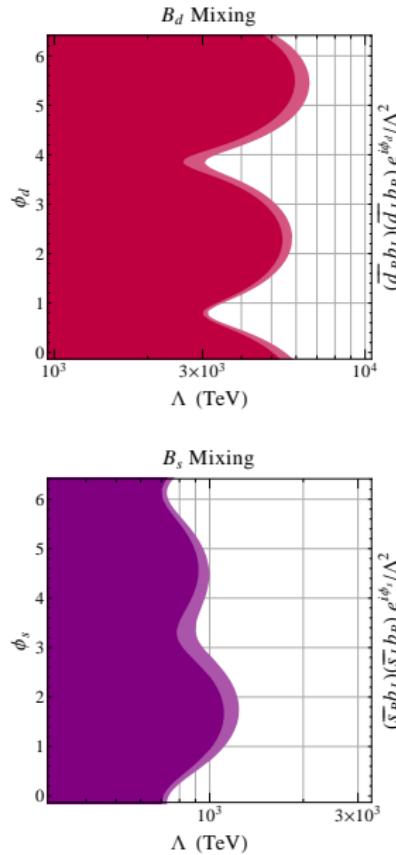
Kaon and Charm Mixing



$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

- ▶ Kaon mixing can probe scales as high as ~ 500.000 TeV
- ▶ Charm mixing probes scales as high as several 10.000 TeV
- ▶ bounds on CP violation in charm mixing can improve by ~ 1 order of magnitude (Belle II with $50 ab^{-1}$)
- ▶ NP at the TeV scale has to have a highly non-generic flavor structure

B_d and B_s Mixing



$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

- B_d and B_s mixing can probe scales of O(1000 TeV - 10.000 TeV)
- Constraints from CP violation in B mixing still can improve by some extent
- NP at the TeV scale has to have a highly non-generic flavor structure

Example: Implications for Higgs Couplings

D^0 oscillations [48]	$ Y_{uc} ^2, Y_{cu} ^2$	$< 5.0 \times 10^{-9}$
	$ Y_{uc}Y_{cu} $	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$ Y_{db} ^2, Y_{bd} ^2$	$< 2.3 \times 10^{-8}$
	$ Y_{db}Y_{bd} $	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$ Y_{sb} ^2, Y_{bs} ^2$	$< 1.8 \times 10^{-6}$
	$ Y_{sb}Y_{bs} $	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\text{Re}(Y_{ds}^2), \text{Re}(Y_{sd}^2)$	$[-5.9 \dots 5.6] \times 10^{-10}$
	$\text{Im}(Y_{ds}^2), \text{Im}(Y_{sd}^2)$	$[-2.9 \dots 1.6] \times 10^{-12}$
	$\text{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \dots 5.6] \times 10^{-11}$
	$\text{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \dots 2.8] \times 10^{-13}$

Blankenburg, Ellis, Isidori '12; Harnik, Kopp, Zupan '12

Avoiding Constraints: Minimal Flavor Violation

Chivukula, Georgi '87; Hall, Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02

- ▶ largest quark flavor symmetry group that commutes with the SM gauge group

$$G_F = SU(3)_Q \otimes SU(3)_U \otimes SU(3)_D \otimes U(1)^3$$

- ▶ the SM Yukawa couplings are the only spurions that break G_F

$$Y_u = 3_Q \times \bar{3}_U, \quad Y_d = 3_Q \times \bar{3}_D$$

- ▶ if new sources of flavor violation are functions of the SM Yukawas, FCNCs are naturally suppressed by small CKM angles and/or small Yukawa couplings
- ▶ NP models with MFV and TeV scale spectrum generically avoid constraints from meson mixing

Examples

- ▶ squark soft masses

$$m_Q^2 = \tilde{m}_Q^2 (\mathbb{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + \dots)$$

$$m_U^2 = \tilde{m}_U^2 (\mathbb{1} + b_3 Y_u^\dagger Y_u + \dots)$$

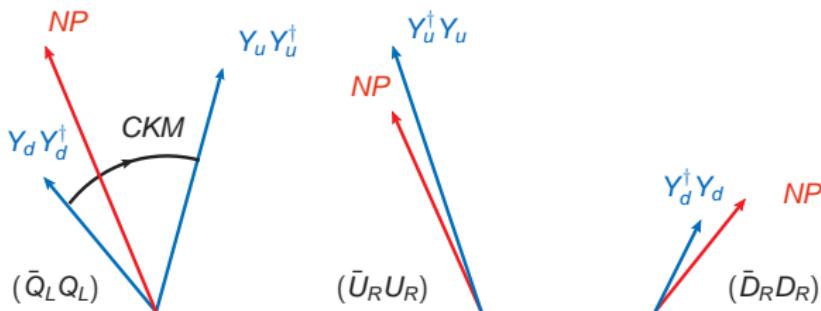
$$m_D^2 = \tilde{m}_D^2 (\mathbb{1} + b_4 Y_d^\dagger Y_d + \dots)$$

- ▶ couplings in a 2HDM

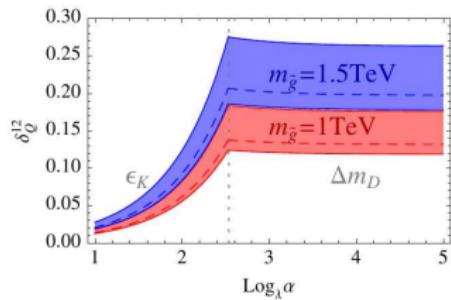
$$\begin{aligned} \tilde{Y}_u &= Y_u (\epsilon_u \mathbb{1} + \epsilon'_u Y_u^\dagger Y_u \\ &\quad + \epsilon''_u Y_d Y_d^\dagger + \dots) \end{aligned}$$

$$\begin{aligned} \tilde{Y}_d &= Y_d (\epsilon_d \mathbb{1} + \epsilon'_d Y_d^\dagger Y_d + \\ &\quad + \epsilon''_d Y_u Y_u^\dagger + \dots) \end{aligned}$$

Avoiding Constraints: Alignment



- ▶ new flavor structures can be aligned with the SM Yukawa couplings (e.g. U(1) flavor symmetries)
- ▶ in the right-handed sector: perfect alignment is in principle possible
- ▶ in the left-handed sector: alignment *either* in the up-direction *or* the down direction
- ▶ combination of Kaon mixing and charm mixing leads to constraints
- ▶ example: mass splitting between 1st and 2nd generation of left-handed squarks



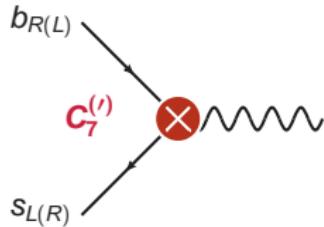
Nir, Seiberg '93;
Blum, Grossman, Nir, Perez '09;
Gedalia, Kamenik, Ligeti, Perez '12; ...

Rare B Decays

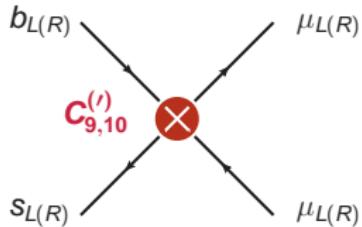
Rare B Decays

$$\mathcal{H}_{\text{eff}}^{b \rightarrow s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C'_i \mathcal{O}'_i \right)$$

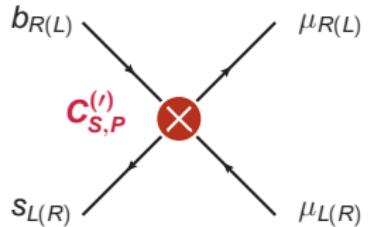
magnetic dipole operators



semileptonic operators



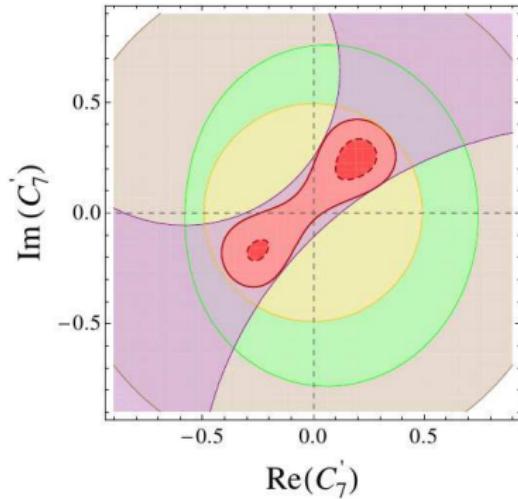
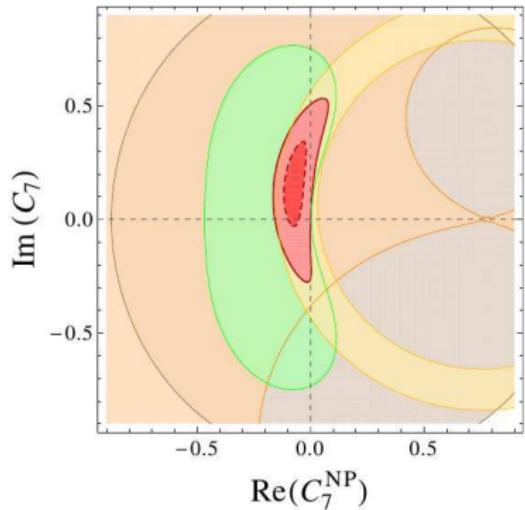
scalar operators



	C_7, C'_7	C_9, C'_9	C_{10}, C'_{10}	C_S, C'_S, C_P, C'_P	
$B \rightarrow (X_s, K^*) \gamma$	★				neglecting tensor operators
$B \rightarrow (X_s, K, K^*) \ell^+ \ell^-$	★	★	★		
$B_s \rightarrow \mu^+ \mu^-$			★	★	

Model Independent Constraints

WA, Straub '12



- ▶ $BR(B \rightarrow X_s \ell^+ \ell^-)$
(both low and high q^2 region)
- ▶ $A_{CP}(B \rightarrow X_s \gamma)$
- ▶ $B \rightarrow K^* \mu^+ \mu^-$
(BR, A_{FB}, F_L, S_3 low and high q^2 region)
- ▶ $BR(B \rightarrow X_s \gamma)$
- ▶ $B \rightarrow K^* \gamma$ (time dep. CP asymmetry)

Implications for the NP Scale

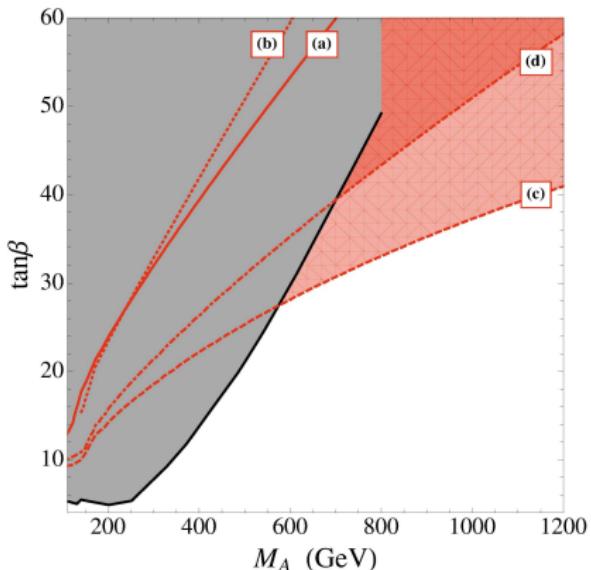
$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \sum_i \left(\frac{c_i}{\Lambda_{\text{NP}}^2} \mathcal{O}_i + \frac{c'_i}{\Lambda_{\text{NP}}^2} \mathcal{O}'_i \right)$$

Operator	Λ_{NP} (TeV) for $ c_i^{(\prime)} = 1$			
	+	-	+i	-i
$\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$	74	188	50	40
$\mathcal{O}'_7 = (\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$	49	70	79	50
$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$	30	57	21	22
$\mathcal{O}'_9 = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$	59	22	21	23
$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	39	37	22	22
$\mathcal{O}'_{10} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	26	68	23	22
$\mathcal{O}_S - \mathcal{O}'_S = \frac{m_b}{m_{B_S}}(\bar{s}\gamma_5 b)(\bar{\ell}\ell)$	91	91	95	95
$\mathcal{O}_P - \mathcal{O}'_P = \frac{m_b}{m_{B_S}}(\bar{s}\gamma_5 b)(\bar{\ell}\gamma_5 \ell)$	113	57	91	91

update from WA, Straub '12

$B_s \rightarrow \mu^+ \mu^-$ in the MSSM with Large $\tan \beta$

WA, Carena, Shah, Yu '12



all squarks degenerate $\tilde{m} = 2\text{TeV}$, $|A_t|$ such that $M_h = 125\text{GeV}$

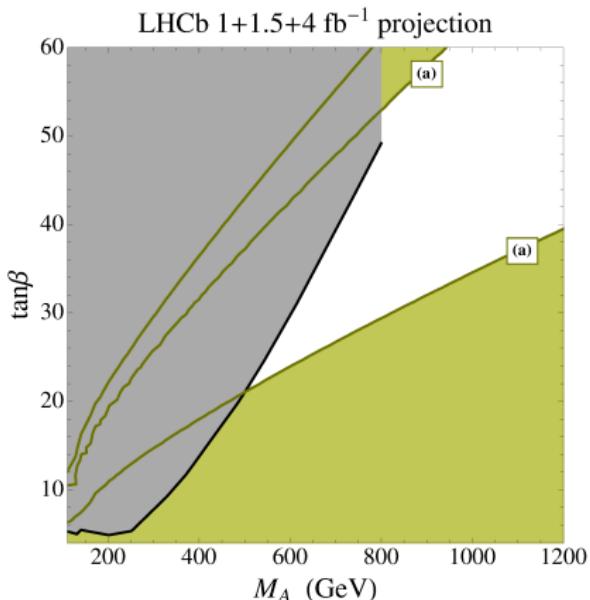
- even for completely flavor blind soft terms, Higgsino stop loops can give huge contributions to $B_s \rightarrow \mu^+ \mu^-$

$$C_S^{\tilde{H}} \simeq -C_P^{\tilde{H}} \propto \frac{y_t^2}{16\pi^2} \frac{\mu A_t}{m_t^2} \frac{\tan \beta^3}{M_A}$$

- for $\mu A_t > 0$ destructive interference of Higgsino loop with SM amplitude
- for $\mu A_t < 0$ constructive interference of Higgsino loop with SM amplitude
→ currently stronger constraint

$B_s \rightarrow \mu^+ \mu^-$ in the MSSM with Large $\tan \beta$

WA, Carena, Shah, Yu '12



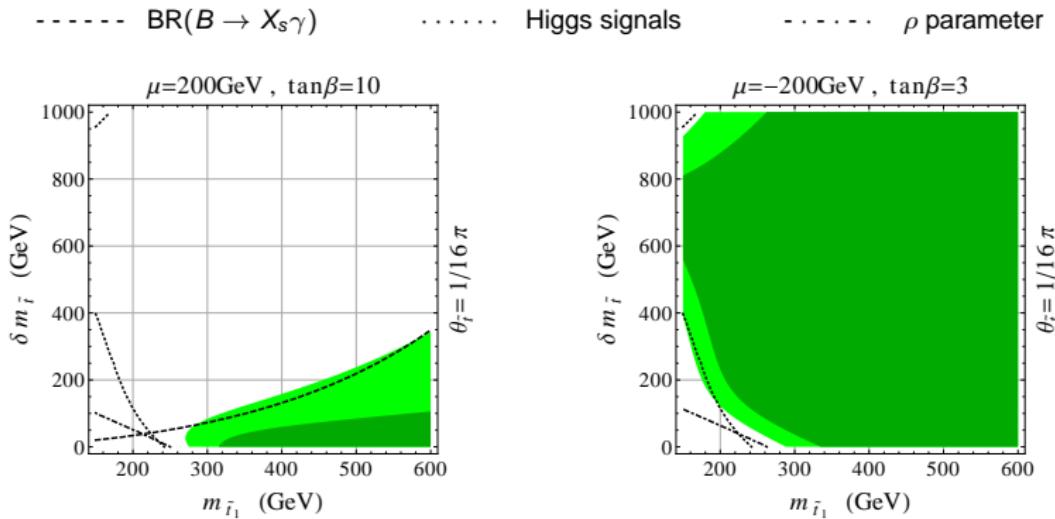
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- for $\mu A_t > 0$ destructive interference of Higgsino loop with SM amplitude
- for $\mu A_t < 0$ constructive interference of Higgsino loop with SM amplitude
→ currently stronger constraint
- projected LHCb sensitivity
 $\delta BR \sim 0.5 \times 10^{-9}$

$B \rightarrow X_s \gamma$ and Light Stops



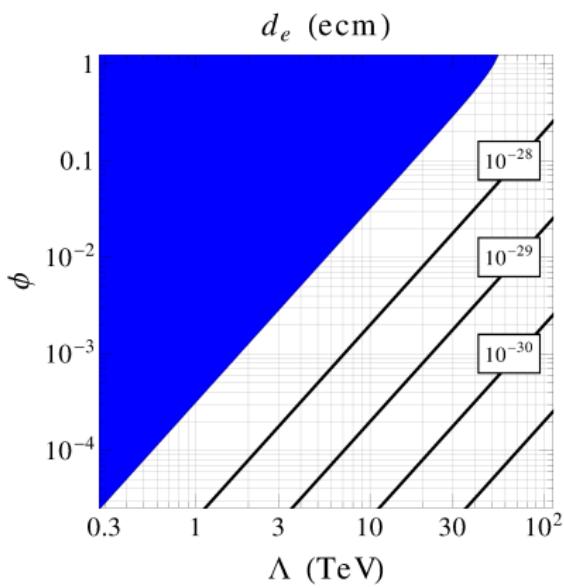
WA, Haisch, in preparation

- $\text{BR}(B \rightarrow X_s \gamma)$ can give strong constraints on light stops
- but: due to possible cancellations, no model-independent lower bound on the stop mass can be found from indirect constraints

$$C_7^{\tilde{t}} \propto \frac{5}{144} \frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{2}{9} \frac{\mu m_t}{m_{\tilde{t}_1}^2} \tan\beta \sin 2\theta_{\tilde{t}}$$

Electric Dipole Moments

Model Independent Constraints from EDMs



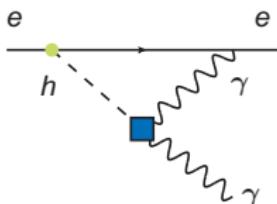
$$\frac{e^{i\phi}}{\Lambda^2} y_e v (\bar{e} \sigma F i\gamma_5 e)$$

- ▶ EDMs are usually loop suppressed
- ▶ proportionality to light fermion Yukawas can be enforced by MFV
- ▶ in presence of generic flavor violation:
 $y_f \rightarrow O(1)$
- ▶ CP phases at the TeV scale are generically constrained to be tiny
 $\phi \lesssim O(10^{-3})$
- ▶ EDM constraints can still improve by several orders of magnitude!

Electric Dipole Moments and the Higgs

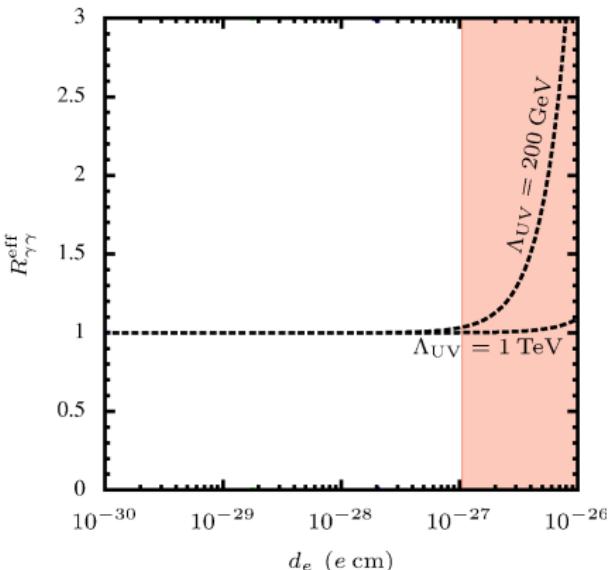
- CPV in $h \rightarrow \gamma\gamma$
strongly related to EDMs

$$\frac{\tilde{C}_v}{\Lambda^2} h F_{\mu\nu} \tilde{F}^{\mu\nu} + y_e h \bar{e} e$$



$$\rightarrow \frac{d_e}{e} = \frac{\tilde{C}}{4\pi^2} m_e \frac{1}{\Lambda^2} \log \left(\frac{\Lambda_{UV}^2}{m_h^2} \right)$$

⇒ possible effects of the $hF\tilde{F}$ operator in $h \rightarrow \gamma\gamma$ are highly constrained by EDMs



(adapted from McKeen, Pospelov, Ritz '12)

- ▶ FCNC processes and EDMs lead generically to strong constraints on possible new sources of flavor and CP violation at the TeV scale
 - *NP Flavor and CP Problem*
- ▶ Flavor non-universalities at the TeV scale are allowed if they are approximately aligned with the SM Yukawas
- ▶ Flavor and CP constraints are indirect
 - accidental cancellations cannot be excluded